Aging and Stability of GaN High Electron Mobility Transistors and Light-Emitting Diodes With TiB_2- and Ir-Based Contacts

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(Invited Paper)

***Abstract*—There is interest in developing more stable contacts to a variety of GaN-based devices. In this paper, we give two examples of devices that show improved thermal stability when boride or Ir diffusion barriers are employed in ohmic-contact stacks. AlGaN/GaN high electron mobility transistors (HEMTs) were fabricated with Ti/Al/X/Ti/Au source–drain ohmic (where X is TiB_2 or Ir) contacts and were subjected to long-term annealing at 350 °C. By comparison with companion devices with conventional Ti/Al/Ni/Au ohmic contacts, the HEMTs with boride-based ohmic metal showed superior stability of both source–drain current and transconductance after 25 days of aging at 350 °C. The gate current for standard HEMTs increases during aging, and the standard ohmic contacts eventually fail by shorting to the gate contact. Similarly, InGaN/GaN multiple quantum well light-emitting diodes (MQW-LEDs) were fabricated with either Ni/Au/TiB_2/Ti/Au or Ni/Au/Ir/Au p-ohmic contacts. Both of these contacts showed superior long-term thermal stability compared to LEDs with conventional Ni/Au contacts.**

***Index Terms*—Gallium Nitride (GaN), high electron mobility transistors (HEMTs), light-emitting diodes (LEDs), ohmic contacts, reliability testing.**

I. Introduction

THERE IS a strong interest in the development of more reliable and thermally stable ohmic contacts on GaN-based electronic devices such as high electron mobility transistors (HEMTs) [1]–[16] and light-emitting diodes (LEDs) [17]–[21]. HEMTs are being commercialized for applications in power amplifiers in S-band to V-band radar and communication systems [11]–[16]. InGaN/GaN multiple quantum well LEDs (MQW-LEDs) are commercially available in a broad range of wavelengths for use in applications such as full color displays, traffic signals, and exterior lighting [17]–[21]. To compete with fluorescent and other high-efficiency lighting sources, the GaN-based LEDs must be driven at high current densities to maximize light output. A drawback of high current densities is the self-heating of the heterostructure which can produce ohmic-contact degradation and generation of nonradiative recombination centers. The common theme in these applications is the need for stable ohmic contacts [22], [23].

The most common n-type ohmic metallization for AlGaN/GaN HEMTs and nitride gas sensors is based on Ti/Al. This bilayer must be deposited with overlayers of Ni, Ti, or Pt followed by Au to reduce sheet resistance and decrease oxidation during the high temperature anneal needed to achieve the lowest specific contact resistivity. These contacts produce low specific contact resistances when annealed in the 750 °C–900 °C range, but there are concerns about the long-term stability during high temperature operation, in part because, if the metal layers begin to intermix, a low-melting-temperature $AlAu_4$ phase that can lead to contact shorting at small electrode separations may form. One solution is to use a very high-melting-point diffusion barrier in place of the Pt, Ni, or Ti in the contact stack. For improving the thermal stability of ohmic contacts, there is interest in higher melting-temperature metals, including W, WSi_X, Mo, V, and Ir. Another promising metallization system as the diffusion barrier layer is based on borides of Cr, Zr, Hf, Ti, or W [9], [10], [16], [20]. Stoichiometric diborides have high melting temperatures (e.g., 3200 °C for ZrB_2) and thermodynamic stability that are at least as good as comparable nitrides [22], [23].

Similarly for LEDs, the conventional metallization schemes used for making ohmic contacts to p-GaN are based on Ni, Pd, Cr, or Pt with an overlayer of Au to reduce the sheet resistance. Specific contact resistances of $\sim 10^{-2}–10^{-4}\ \Omega \cdot cm^2$ are obtained after annealing at 450 °C–650 °C [17]–[19]. These contacts have stability problems at high temperature as the initial Au/Ni/GaN structure transforms to Ni/Au/GaN with a rough Ni surface with annealing at 600 °C. Once again, to prevent excessive intermixing and contact morphology degradation, a

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good approach is to use a high-melting-point diffusion barrier in the contact stack.

In this paper, we report on the use of boride or Ir diffusion barriers in ohmic contacts for HEMTs or LEDs to improve the stability of these devices during extended aging at elevated temperatures. The lifetime prediction for compound semiconductor device operation is notoriously inaccurate due to the fragmented efforts in reliability and absence of standard protocols and has usually relied on accelerated testing at elevated temperatures and then extrapolation back to room-temperature operation. This technique often fails for scaled high-current-density devices. Device failure may be driven by electric fields, current mechanisms, or low activation energy processes that are masked by other mechanisms at high temperature.

II. Experimental Details

For HEMT fabrication, the layer structures were grown on sapphire substrates by molecular beam epitaxy and employed a low temperature AlN (300 Å thick) buffer, 2 μm of undoped GaN grown at 750 °C under Ga-rich conditions, 250 Å of undoped $Al_{0.2}Ga_{0.8}N$, and a 30-Å undoped GaN cap. Mesas were formed by Cl_2/Ar inductively coupled plasma etching to provide the electrical isolation of the contact pads. A Ti/Al/X/Ti/Au metallization scheme annealed at 900 °C, where X was either Ir or TiB_2, was used to form ohmic contacts to n-type GaN. Ni/Au contacts were used for the gate. All of the metals were deposited by Ar plasma-assisted RF sputtering at pressures of 15–40 mTorr and RF (13.56 MHz) powers of 200–250 W. The contacts were patterned by liftoff. The contact properties were obtained from linear transmission-line-method measurements on $100 \times 100 - \mu$m pads with spacing of 5, 10, 20, 40, and 80 μm. The HEMT dc characteristics were measured with an HP 4145B parameter analyzer.

The MQW-LED structures were grown by metal organic chemical vapor deposition on c-plane sapphire substrates. The layer structure consisted of a low-temperature GaN buffer, 3-μm-thick n-GaN, 0.1-μm n-AlGaN clad, three-period undoped InGaN/GaN MQW active, 0.1-μm p-AlGaN clad, and 0.3-μm p-GaN layer. Ohmic contacts to n-GaN were formed by the liftoff of e-beam deposited Ti (20 nm)/Al (80 nm)/Pt (40 nm)/Au (80 nm) that were subsequently annealed at 800 °C for 1 min in a flowing N_2 ambient in a rapid-thermal-annealing furnace. The first p-metallization scheme investigated consisted of Ni (50 nm)/Au (80 nm)/Ir (50 nm)/Au (80 nm). The second contact scheme was Ni (50 nm)/Au (80 nm)/TiB_2 (50 nm)/Ti (20 nm)/Au (80 nm). The Ni/Au layers were deposited by e-beam evaporation, whereas the Ir/Au and $TiB_2/Ti/Au$ overlayers were deposited by Ar plasma-assisted RF magnetron sputtering. For comparison, devices with Ni/Au contacts were also fabricated by using the same wafer. All contacts were patterned by the liftoff of lithographically defined photoresist and annealed at 600 °C for 1 min in a flowing N_2 ambient. All devices were first aged for a period of 10 days at 200 °C on a heater plate in air. The samples were removed from the heater block, allowed to cool to room temperature, and characterized before being returned for a further 35-day aging at 350 °C. MQW-LEDs were analyzed by luminescence–current–voltage

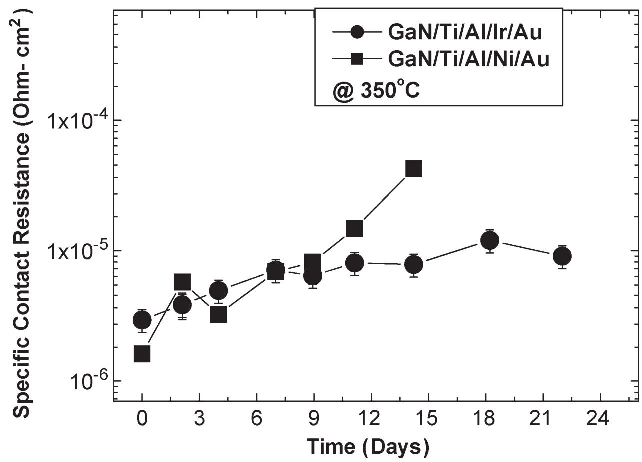

Fig. 1. Specific contact resistance of the Ti/Al/Ni/Au and Ti/Al/Ir/Au contacts annealed at 900 °C as a function of aging time at 350 °C.

(L–I–V) measurements using a probe station and an Agilent 4145B parameter analyzer. The light output power was measured by using a Si photodetector located at ∼2 cm from the sample surface.

III. Results and Discussion

A. HEMT Contacts

Fig. 1 shows the room-temperature ohmic-contact resistance on HEMT samples with either standard or Ir-based contacts annealed at 800 °C as a function of time spent at 350 °C. Each data point represents the average of four measurements on different devices. This simulates the operation of an uncooled GaN-based transistor and gives some idea of the expected stability of the contact. Note that the latter shows the lowest initial contact resistance but then has an increase of almost an order of magnitude after nine days of elevated temperature operation. By contrast, the devices with Ir diffusion barriers show less change with aging time and have lower contact resistances than the Ti/Al/Ni/Au after 22 days of aging at 350 °C. The same basic trends were observed with the TiB_2 diffusion-barrier contacts. This suggests that the improved stability of the Ir and TiB_2 relative to Ni has some beneficial effect on the long-term stability of the contacts.

Fig. 2 shows an Arrhenius plot of the HEMT gate current at a fixed bias as a function of aging time at 350 °C for devices with conventional contacts. Prior to aging, the device shows a thermally activated current with an activation energy of ∼0.58 eV. We presume that the origin of this value comes from the emission from electron traps in the buffer layer, as we discuss next. On the aged devices, there is a significant increase in the drain current at moderate temperatures as the contact resistance increases. By contrast, HEMTs with the Ir or TiB_2 contacts did not show this increase in gate current over the aging period, with the values remaining basically similar to that of unaged devices.

The scanning-electron-microscope (SEM) images of the standard HEMTs before and after aging to failure (no device functionality) are shown in Fig. 3. The ohmic-contact metallurgy has shorted to the gate metal on the failed devices. This

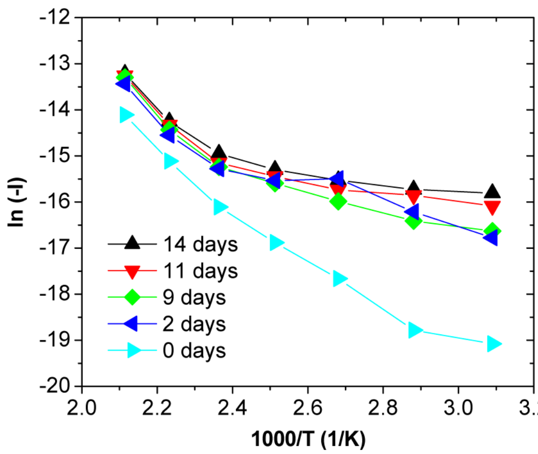

Fig. 2. Arrhenius plot of gate current for HEMTs with conventional contacts as a function of aging time at 350 °C.

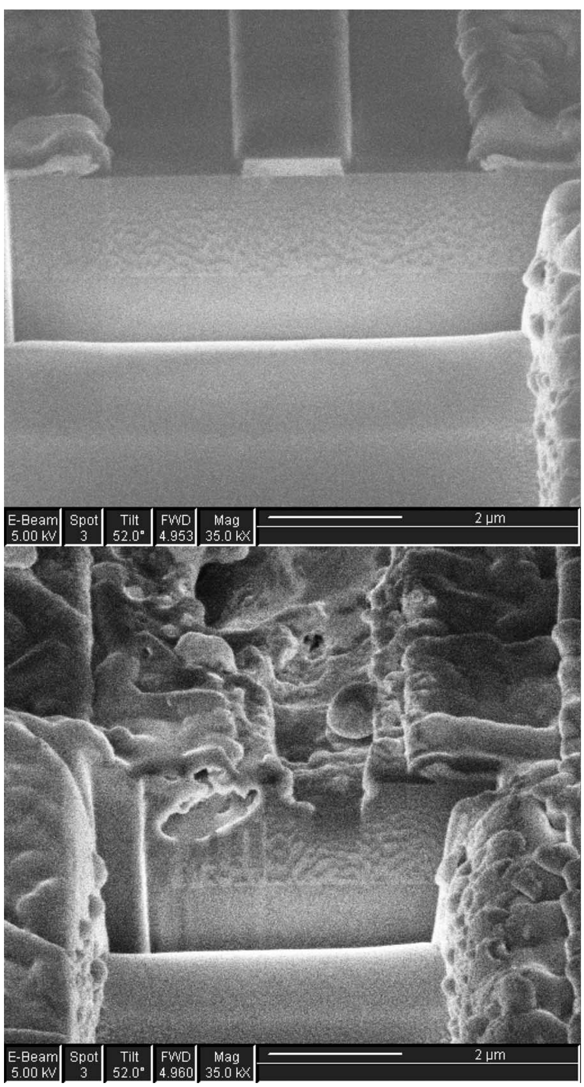

Fig. 3. SEM images of HEMTs with conventional contacts before and after aging to failure.

is consistent with the origin of the failure being the formation of the $AlAu_4$ phase mentioned earlier. We did not observe this encroachment in the devices with Ir- or TiB_2-based ohmic contacts, which indicates that these diffusion barriers are more

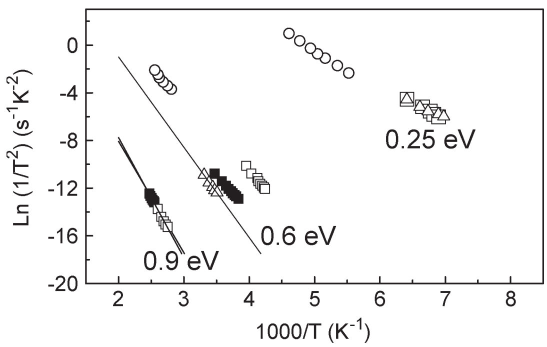

Fig. 4. Arrhenius plot of emission time contact for traps observed in HEMT structures prior to aging.

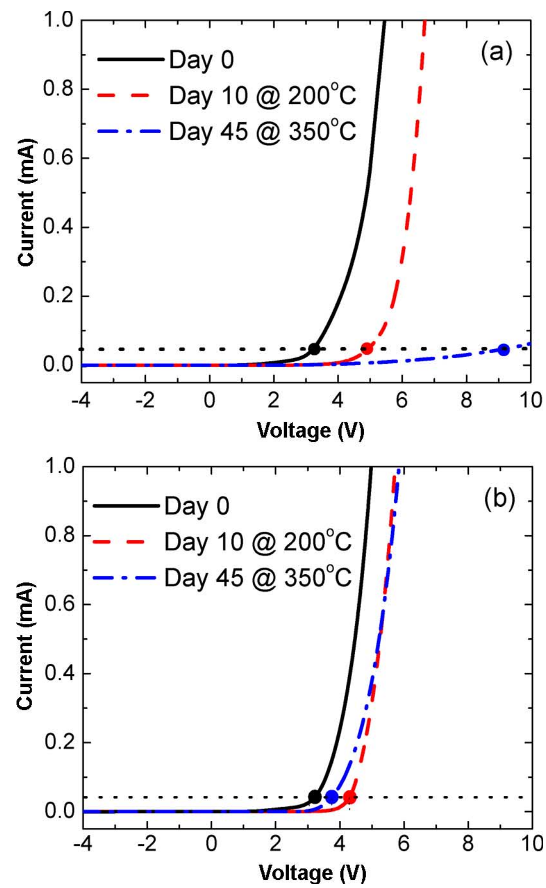

Fig. 5. Influence of long-term aging at 250 °C and 350 °C on the I–V characteristics of LEDs with (a) Ni/Au or (b) Ni/Au/Ir/Au p-ohmic contacts.

effective at maintaining the separation of the individual contact metals.

We performed deep-level transient spectroscopy on large area diodes on the starting HEMT material. Three electron traps were observed with activation energies of 0.25, 0.6, and 0.9 eV, with the 0.6-eV center having the highest signal. Fig. 4 shows the Arrhenius plots for these peaks obtained, as usual, by changing the values of the time windows. Comparison of the deep trap spectra of GaN buffers and Si-doped n-GaN films prepared on GaN buffers suggests that the traps in question are located in the buffer layer. It is likely that the 0.6-eV trap is the cause of the observed activation energy in the drain–current data of unaged HEMTs in Fig. 2. As the ohmic contacts degrade

TABLE I
INFLUENCE OF LONG-TERM AGING AT 200 °C AND 350 °C ON THE TURN-ON VOLTAGE AND REVERSE CURRENT AT-5 V OF MQW-LEDs

Contact scheme	Day 0	Day 10@200°C	Day 45@350°C
Ni/Au	3.3±0.3 V	4.9±0.4 V	9.1±0.5 V
Ni/Au/TiB_2/Ti/Au	3.5±0.2 V	4.1±0.5 V	4.0±0.2 V
Ni/Au/Ir/Au	3.3±0.2 V	4.4±0.3 V	3.9±3.9 V

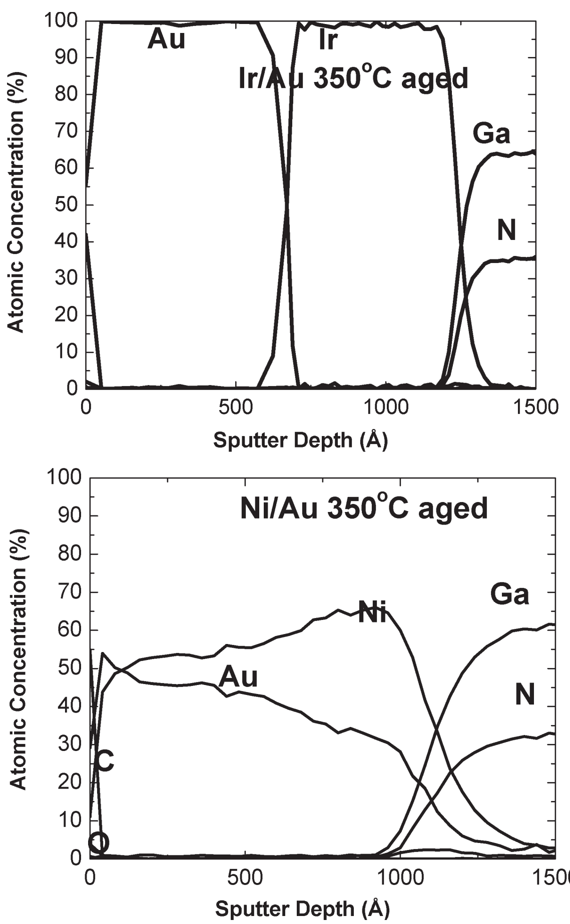

Fig. 6. AES depth profiles of (top) Ir/Au and (bottom) Ni/Au contacts on LEDs after aging at 350 °C.

with aging time at 350 °C, these traps no longer dominate the observed current in the structure.

B. LEDs

The fabricated InGaN/GaN MQW-LEDs had an electroluminescence (EL) peak wavelength of 459 nm with a full width at half maximum of 26 nm. The L–I characteristics were similar for all metallization schemes investigated, showing that the TiB_2/Ti/Au or Ir/Au overlayers did not reduce the light output with respect to the conventional Ni/Au contacts.

I–V characteristics from MQW-LEDs with Ni/Au and Ni/Au/Ir/Au ohmic contacts to the p-GaN layer are shown in Fig. 5. The data for LEDs with Ni/Au/TiB_2/Ti/Au were similar to that for the devices with Ir-based contacts. For all diodes, the ideality factor was > 2, which is consistent with other data reported previously. For as-fabricated devices, the turn-on voltage was 3.2–3.6 V, and the reverse leakage current was $\sim 10^{-6}$ A. Such high leakage currents are commonly observed in GaN-based LEDs grown on sapphire substrates and essentially result from the high density of dislocations in such samples [8]. After ten days of aging at 200 °C, an increase of the turn-on voltage to ~4.1 V and a decrease of the leakage current to $\sim 10^{-9}$ A were observed for all devices. After aging at 350 °C for an additional 30 days, MQW-LEDs with TiB_2- and Ir-based ohmic contacts show turn-on voltages (summarized in Table I) and leakage currents that are similar to those in the as-deposited state, whereas there was serious degradation in LEDs fabricated with Ni/Au contacts. The degradation of Ni/Au contacts upon aging results from the formation of an islanded contact morphology and excessive intermixing of Ni and Au, leading to oxidation on the rough Ni surface. The latter is evident in the Auger electron spectroscopy (AES) depth profiles of Fig. 6 for devices aged at 350 °C. The Ir-based contacts do not show significant intermixing of the metals, whereas the Ni/Au contacts have extensive reactions.

IV. SUMMARY AND CONCLUSIONS

Aging data on HEMTs with Ir or TiB_2 diffusion barriers in the source–drain contacts show a higher resistance to degradation than devices with conventional Ti/Al/Ni/Au contacts. Similarly, LEDs with Ir or TiB_2 diffusion barriers showed improved aging stability compared with devices with conventional contact schemes. More work is needed to determine the contact-degradation mechanisms. In particular, the borides are known to be susceptible to oxidation but the presence of the capping layers may reduce the significance of this issue.

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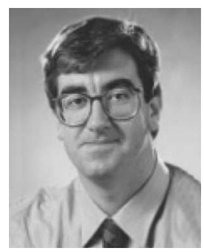

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